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Cosmic Rays and High-Energy Neutrinos from Gamma-Ray Bursts

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Abstract

Several lines of evidence point to a relationship between gamma-ray bursts (GRBs) and the high mass stars that explode as supernovae. Arguments that GRB sources accelerate cosmic rays (CRs) are summarized. High-energy neutrino detection from individual GRBs would mean that they are hadronically dominated, that is, that the amount of energy deposited in the form of nonthermal hadrons in GRB blast waves greatly exceeds the radiated energy inferred from their photon emission spectra. Such a detection would make GRBs the favored candidate sources of ultra-high energy and super-GZK CRs. Cascade radiation induced by high-energy hadrons could be detected from GRBs with γ-ray telescopes.

Key words: Gamma Ray Bursts, Cosmic Rays, Gamma Rays, Neutrinos

1 Introduction

Considerable evidence connects long-duration GRBs to star-forming regions (see (1; 2) for review) and, consequently, to the high-mass stars that radiate strongly in the UV band and evolve to supernova core collapse. For example, the host galaxies of GRBs have blue colors, consistent with galaxy types that are undergoing active star formation. GRB counterparts are found within the optical radii and central regions of the host galaxies. Lack of optical counterparts in approximately one-half of GRBs with well-localized X-ray afterglows (so-called “dark bursts”) could be due to extreme reddening from large quantities of gas and dust in star-forming host galaxies. Supernova-like emissions have been detected in the late-time optical decay curves of a few GRBs including, most recently, the low redshift ($z = 0.17$) GRB 030329 (3).

Furthermore, X-ray features have been detected in about 6 GRBs, which implies the existence of dense, highly enriched material in the vicinity of the

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sources of GRBs (see (4; 5) for review). This includes the variable absorption feature attributed to photoionization of Fe in GRB 990705, Kα and recombination edges from highly ionized Fe and S in the afterglow spectra of GRB 991216, multiple high-ionization emission features detected in GRB 011211 and, at lower significance, claimed X-ray Fe Kα features in GRB 970508, GRB 970828, and GRB 000214.

The association of GRB 980425 and the Type Ic SN 1998bw (6), if true, directly connects GRBs and SNe. The well-measured light curve of SN 1998bw has been used in a number of cases to model reddened excesses in the optical afterglow spectra found tens of days after the GRB, again pointing to a SN/GRB connection.

Because supernovae are widely thought to accelerate galactic cosmic rays, the supernovae associated with GRBs should play a special role in the CR/GRB connection. Here we summarize work connecting CRs, SNe, and GRBs, beginning with source models of GRBs and arguments for CR acceleration by supernovae. High-energy neutrino detection with km-scale telescopes such as IceCube would conclusively establish that hadrons are accelerated by GRBs, and is likely if GRB sources are hadronically dominated by a factor of ≈ 10 or more. This would be required in a GRB model that accelerates nonthermal power-law distributions of particles to produce ultra-high energy cosmic rays (UHECRs) with energies $\gtrsim 10^{18.5}$ eV, and super-GZK CRs with energies $\gtrsim 10^{20}$ eV. Hadronic cascade radiation could make GRBs luminous sources of GeV-TeV emission that would be detectable with *GLAST*, *VERITAS*, and *HESS*.

2 Gamma-Ray Bursts and Supernovae

Leading scenarios for the sources of long-duration GRBs are the collapsar and supranova models. In the former case (7), GRBs are formed in the seconds to minutes following the collapse of the core of a massive star to a black hole. During the collapse process, a nuclear-density, several Solar-mass accretion disk forms and accretes on the newly born black hole at the rate of ~ 0.1-$1\ M_\odot\ \mathrm{s}^{-1}$ to drive a baryon-dilute, relativistic outflow through the surrounding stellar envelope. The duration of the accretion episode corresponds to the period of activity of the relativistic winds that are argued to produce the prompt variable GRB emission. A wide variety of collapsar models are possible (8), but their central feature is the one-step collapse of the core of a massive star to a black hole. A major difficulty of this model is to drive a baryon-dilute, relativistic outflow through the stellar envelope (9).

In the supranova model (10), GRBs are the second in a two-step collapse

process of an evolved massive stellar core to a black hole through the intermediate formation of a neutron star with mass exceeding several Solar masses. The neutron star is initially stabilized against collapse by rotation, but the loss of angular momentum support through magnetic dipole and gravitational radiation leads to collapse of the neutron star to a black hole after some weeks to years. A two-step collapse process means that the neutron star is surrounded by a SN shell of enriched material at distances of $\sim 10^{15}$-10^{17} cm from the central source. The earlier SN could yield ~ 0.1-$1\ M_\odot$ of Fe in the surrounding vicinity to provide a surrounding shell of material that forms prompt and afterglow X-ray features in GRB spectra.

A pulsar wind and pulsar wind bubble consisting of a quasi-uniform, low density, highly magnetized pair-enriched medium within the SNR shell is formed by a highly magnetized neutron star during the period of activity preceding its collapse to a black hole (11). The interaction of the pulsar wind with the shell material will fragment and accelerate the SNR shell, and the pulsar wind emission will be a source of ambient radiation that can be Comptonized to gamma-ray energies (12). The heating of the SN shell by the plerionic emission could give rise to a characteristic cooling shell signature, which might explain some instances of the delayed reddened excesses in optical afterglow spectra (13).

In both the collapsar and supranova models, the stellar progenitors are $\gtrsim 10\mathrm{M}_\odot$ stars that evolve to core collapse and produce a supernova with an expanding nonrelativistic shell, and a GRB with its highly relativistic ejecta. The shocks formed in these nonrelativstic and relativistic outflows can accelerate cosmic rays.

3 Cosmic Rays and Supernovae

The strongest argument that hadronic cosmic rays (CRs) are powered by SNRs is probably the claim that only SNe inject sufficient power into the Galaxy to provide the measured energy density of CRs (14; 15). A time- and volume-averaged kinetic luminosity $\gtrsim 10^{41}$ ergs s^{-1} in the disk of the Milky Way is required to power the galactic CRs. The galactic SN luminosity is $\approx$ (1 SN/30 yrs)$\times 10^{51}$ ergs/SN $\approx 10^{42}$ ergs s^{-1} which, given a 10% efficiency for converting the directed kinetic energy of SNe into CRs that seems feasible through the shock-Fermi mechanism, is adequate to power the cosmic radiation.

Besides available power, Fermi acceleration at SNR shocks offers another strong argument that cosmic rays originate from supernovae. In Fermi models, the directed kinetic energy of a nonrelativistic or relativistic outflow is transferred to a small fraction of suprathermal particles, either through repeated

scattering and diffusion upstream and downstream of the shock front (first-order Fermi acceleration), or through energy diffusion accompanying stochastic pitch-angle scatterings with the magnetic turbulence spectrum (second-order Fermi acceleration).

As compared with some other acceleration mechanisms, for example, charge-depletion fields in pulsar magnetospheres or through magnetic reconnection in stellar flares, the shock-Fermi mechanism naturally produces power-law particle spectra, at least in the test particle approximation. First-order Fermi acceleration at a nonrelativistic strong shock gives the canonical test-particle shock index $s = -2$, and first-order Fermi at a relativistic shock gives the canonical test particle shock index $s \cong -2.2$ (16). Modifying these standard injection indices through energy-dependent diffusion for impulsive, steady, or stochastic injection models offers a wide range of flexibility to explain observations of cosmic rays.

4 Cosmic Rays and Gamma-Ray Bursts

Arguments for a connection between CRs and GRB sources are based on the coincidence between available power of GRBs within the GZK radius and the power required to accelerate super-GZK particles. Moreover, the available power from GRBs within our Galaxy is sufficient to accelerate CRs between the knee at $\approx 3\times10^{15}$ eV and the ankle at $\approx 10^{18.5}$ eV (if these CRs are trapped in the halo of our Galaxy), and could even power a significant fraction of the GeV-TeV/nuc cosmic rays (17).

The Larmor radius of a particle with energy $10^{20}E_{20}$ eV is $\approx 100E_{20}/(ZB_{\mu\mathrm{G}})$ kpc. Unless super-GZK CRs are heavy nuclei, they probably originate from outside our Galaxy. Based on assumptions that the faintest BATSE GRBs are at redshifts $z \approx 1$, it was shown (18; 19) that the energy density of super-GZK CRs is comparable to the energy density that would be produced by GRB sources within the GZK radius, assuming that the measured γ-ray energy from GRBs is roughly equal to the total energy deposited in the form of UHECRs. This coincidence is verified by a detailed estimate of GRB power in the context of the external shock model for GRBs (17; 20). A prediction of this hypothesis is that star-forming galaxies which host GRB activity will be surrounded by neutron-decay halos.

The local density of L^* galaxies like the Milky Way galaxy can be derived from the Schechter luminosity function, and is $\approx 1/(200\text{-}500\ \mathrm{Mpc}^3)$. The BATSE observations imply ~ 2 GRBs/day over the full sky. Due to beaming, this rate is increased by a factor of 500 (21). This implies an event rate of about 1 GRB in the Milky Way every 10^3-10^4 years, and an energy injection rate of $\approx 10^{40\pm1}$

ergs s^{-1} (22). This estimate takes into account the assumption that the GRB rate density follows the star-formation rate history of the universe, and a factor of ≈ 3 to account for the contribution from clean and dirty fireballs, such as the X-ray rich GRBs, for every classical long-duration GRB. Thus the GRB rate is about 10% as frequent as Type Ib/c SNe, and about 1% as frequent as Type II SNe.

Because each GRB has a total energy release of a few $\times 10^{51}$ ergs, a factor of a few greater than the energy release in "normal" SNe, but occurs ~ 100 times less frequently, the available power from the sources of GRBs is a few per cent of the power from Type Ia and Type II SNe. The efficiency for accelerating CRs in the relativistic outflows of GRBs could be much greater than in nonrelativistic SNe, so that the progenitor sources of GRBs could make a significant contribution to CRs at all energies.

From the rate estimates, we see that about 1 in 10 to 1 in 100 SNRs would exhibit this enhanced emission from strong CR acceleration due to an associated GRB. The better imaging and sensitivity of the *GLAST* telescope and the next generation of imaging ground-based air Cherenkov telescopes, namely VERITAS, HESS and MAGIC, will test this hypothesis.

5 High-Energy Neutrinos from GRBs

Detection of high-energy neutrinos from km-scale telescopes such as IceCube will establish hadronic acceleration in sources such as blazars and GRBs. We (23) have recently completed the first quantitative set of calculations of photomeson neutrino production for the collapsar and supranova models of GRBs that also treats associated $\gamma\gamma$ pair-production attenuation of the emergent γ-ray emission. This model takes into account nonthermal proton injection followed by photomeson energy loss, based on our photo-hadronic model for blazar jets (24). The basic assumption in our calculations is that equal kinetic energy is injected in nonthermal protons as is measured in hard X-ray and soft γ-ray photons. Given the fluence of a GRB, the energy injected in protons therefore depends only on the Doppler factor δ.

Neutrinos will be formed through photomeson production with internal synchrotron radiation and, in the supranova model, with external synchrotron photons emitted by the pulsar wind electrons. Even with the very strong radiation field that could occur in the supranova model, model-independent arguments (23), which we reproduce here, show that it is not possible under the assumption of equal energy in hadrons and observed radiation to detect neutrinos from any GRBs except those exceedingly rare events at the level $\gtrsim 3 \times 10^{-4}$ ergs cm^{-2}, which occur about 2-5 times per year (25).

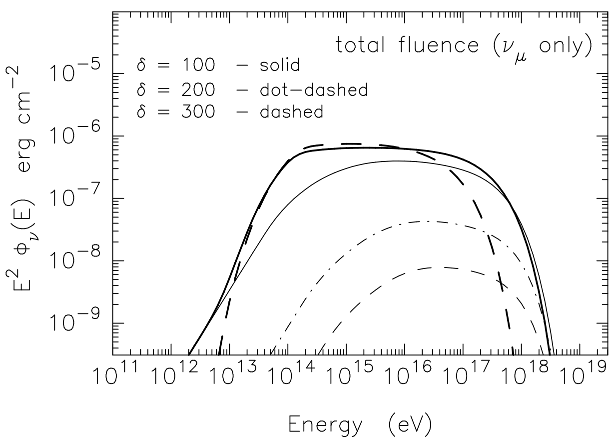

Fig. 1. Energy fluence of photomeson muon neutrinos for a model GRB (23). The thin curves show collapsar model results where only the internal synchrotron radiation field provides a source of target photons. The thick curves show the $\delta = 100$ and 300 results for the supranova model calculation, which includes the effects of an external pulsar wind radiation field.

The detection efficiency in water or ice of ultrarelativistic upward-going muon neutrinos (ν_μ) with energies $\epsilon_\nu = 10^{14}\epsilon_T$ eV is $P_{\nu\mu} \cong 10^{-4}\epsilon_T^{\chi}$, where $\chi = 1$ for $\epsilon_T < 1$, and $\chi = 0.5$ for $\epsilon_T > 1$ (26). For a neutrino fluence spectrum parameterized by $\nu\Phi_\nu = 10^{-4}\phi_{-4}\epsilon_T^{\alpha_\nu}$ erg cm^{-2}, the number of ν_μ detected with a km-scale ν detector such as IceCube with area $A_\nu = 10^{10}A_{10}$ cm^2 is therefore

$$N_\nu(\geq \epsilon_T) \approx \int_{\epsilon_T}^{\infty} \mathrm{d}\epsilon_1\, \frac{\nu\Phi_\nu}{\epsilon_1^2}\, P_{\nu\mu}A_\nu \simeq 0.6\, \frac{\phi_{-4}A_{10}}{\frac{1}{2}-\alpha_\nu} \begin{cases} g_{\alpha_\nu}(\epsilon_T)\ , & \text{for } \epsilon_T < 1 \\ \epsilon_T^{\alpha_\nu - 1/2}\ , & \text{for } \epsilon_T \gtrsim 1\ , \end{cases} \tag{1}$$

where $g_{\alpha_\nu}(\epsilon_T) = 1 + [(1/2\alpha_\nu) - 1](1 - \epsilon_T^{\alpha_\nu})$. For a $\nu\Phi_\nu$ spectrum with $\alpha_\nu \simeq 0$, the number of ν_μ to be expected are $N_\nu \simeq 1.2\phi_{-4}A_{10}(1 + \frac{1}{2}\ln\epsilon_T^{-1})$ for $\epsilon_T < 1$, and $N_\nu \simeq 1.2\phi_{-4}A_{10}/\sqrt{\epsilon_T}$ for $\epsilon_T > 1$. Thus, if the nonthermal proton energy injected in the proper frame is comparable to the radiated energy required to form GRBs with hard X-ray/soft γ-ray fluences $\gtrsim 10^{-4}$ ergs cm^{-2}, then extremely bright GRBs are required to leave any prospect for detecting ν_μ with km-scale neutrino detectors. This estimate does not take into account the loss of efficiency to produce ν_μ from energetic protons through photomeson processes, so the number of ν_μ detected from individual GRBs would be even less.

Fig. 1 shows the total ν_μ fluences expected from a model GRB with a photon fluence of 3×10^{-5} ergs cm^{-2} that is radiated in 50 one-second pulses. The variability time scale determines the size scale of the emitting region given δ, and thus the intensity of internal synchrotron photons for photomeson production. The thin curves show collapsar model results at $\delta = 100$, 200, and 300. The expected numbers of ν_μ that a km-scale neutrino detector would detect are

$N_\nu = 3.2 \times 10^{-3}$, 1.5×10^{-4}, and 1.9×10^{-5}, respectively. The heavy solid and dashed curves in Fig. 1 give the supranova model predictions of $N_\nu = 0.009$ for both $\delta = 100$ and $\delta = 300$. The equipartition magnetic fields used in this calculation are 1.9 kG and 0.25 kG, respectively. The external radiation field in the supranova model makes the neutrino detection rate insensitive to the value of δ (as well as to the variability time scale, as verified by calculations). As the above estimate shows, there is no prospect to detect ν_μ from GRBs at this levels or from a GRB with a factor of ten more fluence.

Although this calculation is not optimistic for neutrino detection, note that the coincidence between the power released by GRBs in γ rays within the GZK radius and the power required for the super-GZK CRs assumes that equal energy is injected into the highest energy cosmic rays as is detected as GRB photon radiation. This is possible in a second-order Fermi acceleration scheme where a very hard, very high energy particle population is produced (27). If particles are instead injected with a -2 or -2.2 spectrum through a first-order Fermi mechanism, then GRBs must be hadronically dominated if they are to power the UHECRs. Thus, $\approx$ 10-100 times as much power must be injected in hadrons as is inferred from the hard X-ray/soft γ-ray emission from GRBs. Under these conditions, IceCube could expect to detect high-energy neutrinos from several GRBs each year. Such a discovery would have a profound impact on our understanding of cosmic rays. In addition, luminous MeV-GeV-TeV cascade radiation induced by hadronic secondaries would be produced. Observations of distinct γ-ray components in GRB spectra would also support the GRB/CR connection.

6 Conclusions

Many lines of evidence point to a close linkage between supernovae, gamma-ray bursts, and cosmic rays. Detection of high-energy neutrinos from the sources of GRBs would confirm hadron acceleration to very high energies. Under the assumption that equal energy is injected into protons as is measured in radiation, we have found (23) that there is no realistic prospect for neutrino detection except from the most fluent GRBs at a level $\gtrsim 3 \times 10^{-4}$ ergs cm^{-2}. More optimistic estimates from the viewpoint of detecting GRB neutrinos could be found in proton-dominated GRB models. Without this hypothesis only the brightest GRBs can be expected to be detected with both high-energy γ-ray and neutrino detectors. The assumption of hadronically dominated GRBs is required to provide the required energy in UHECRs if the protons are accelerated in the form of a power law with number index steeper than -2. Detection of high-energy neutrinos from GRBs would test scenarios for GRBs, the hypothesis that GRBs sources are powerful accelerators of ultrarelativistic CRs, and our understanding of the origin of GRB radiation.

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